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Volcanoes in the Adriatic Sea: Permo-Triassic magmatism on the Adriatic–Dinaridic carbonate platform

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1. Introduction

The Mesozoic Adriatic-Dinaric carbonate platform, a unique geological formation, stretches along the present Adriatic coast. It consists of autochtonous and allochtonous geotectonic elements as Outer or External Dinarides, known also as the High Karst Zone, and less tectonically disturbed parts in Istria, in the Central Adriatic, Ravni Kotari, etc. It is a part of the Alpine–Himalayan orogenic belt with complex evolution of the passive Gondwana continental margins, whose formation can be traced from the Carboniferous to the termination

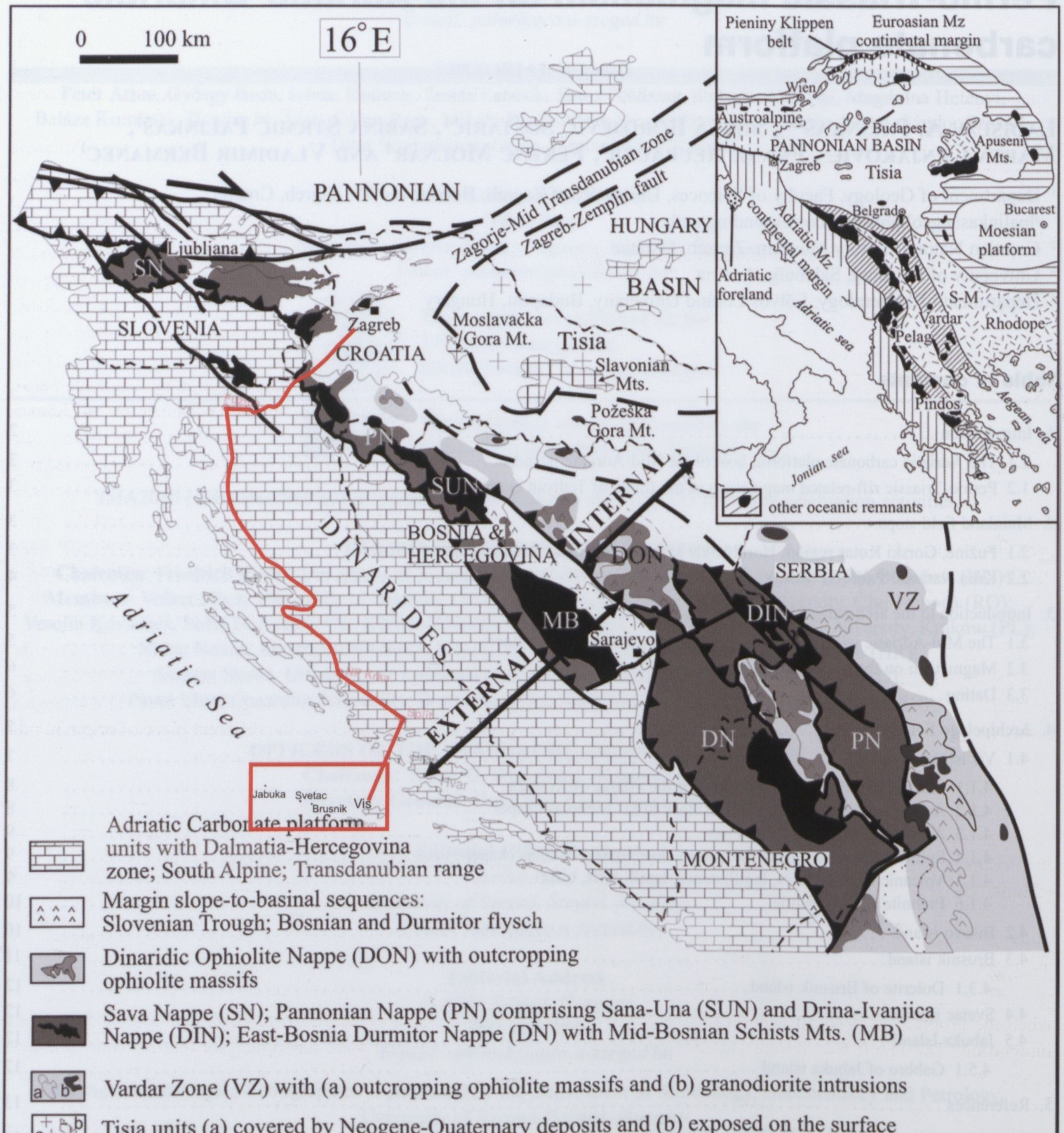


Fig. 1. Geological sketch of the Dinarides and their major geotectonic units with the schematic route of the field trip from Zagreb to Split and to the Mid-Adriatic islands.

in the Paleogene, and then distraction during uplift in the Neogene. Interesting phenomena of karst geomorphology, used in the international karst terminology, owe their names to the local toponyms, such as "doline" and "polje". Even the term "karst" came from "kras" or "krš", meaning "rough" or "rugged". The lovely landscape of the Adriatic coast owes its appearance to the white carbonate rocks shaped by neotectonics and karst weathering. However, the focus of the field trip is not the carbonate platform itself, and its unique characteristics. The field trip will pay attention to the unusual islands, Vis, Jabuka and Brusnik, built exclusively or partly of igneous rocks, intrusives and volcanics with puzzling position in the Mid-Adriatic Sea, within the platform sedimentary units. The unique carbonate deposition in the Adriatic carbonate platform, which reached sediment thickness of 8000 m in the Outer Dinarides, incorporated strange igneous formations (Fig. 1, Crnjaković, 1998). It raises the question: Why and when volcanoes disturbed the quiet environment of shallow waters on the carbonate platform?

1.1 The Adriatic carbonate platform, host of the Mid-Adriatic islands

The name Adriatic plate is defined as an area occupied by the Adriatic Sea and by the surrounding Periadriatic mountain belts (Apennines, Alps, Dinarides and Hellenides), commonly interpreted as the deformed margin of the Adriatic plate itself (Fig. 1). The geotectonic position of the islands is tightly connected with the destiny of the Adriatic plate, a promontory of the African craton (D'Argenio *et al.*, 1980). The Mesozoic and Cenozoic evolution of the Adriatic plate (Outer Dinarides and Adriatic foreland) is still a matter of debate. The question under discussion is: Single carbonate platform (Adriatic–Dinaridic) versus two carbonate platforms (Adriatic and Dinaridic) separated by the inter-platform Budva–Cukali basin (Korbar, 2009). According to Vlahović *et al.* (2005), a huge epeiric carbonate platform developed along the passive Gondwana margin by mixed siliciclastic-carbonate deposition as early as the Carboniferous. Its existence was persisting till the Middle Triassic, when tectonic paroxysm, in response to the advanced stage of Tethyan rifting, created a megaplatform, being departed from the Gondwanian cratonic hinterland. Widespread Middle Triassic magmatism accompanied rifting. The megaplatform survived as an entity up to the Late Triassic/Early Jurassic, when the progressive Tethyan oceanization initiated its disintegration. The result was several smaller carbonate platforms, Adriatic, Apenninic and Apulian platforms, separated by newly established marine areas, as Adriatic, Belluno, and Lagonero basins, and Slovenian and Bosnian troughs. The end of the Adriatic carbonate platform deposition is marked by a regional emergence between the Cretaceous and the Palaeogene.

1.2 Permo-Triassic rift-related magmatism in the frame of Tethyan evolution

Permo-Triassic rift-related magmatism in the Dinarides produced a gabbro-diorite-syenite-granite formation and an extrusive basalt-andesite-dacite formation with abundant pyroclastic rocks (Pamić & Balen, 2005). The volcanic and pyroclastic rocks are interlayered with fossiliferous sediments from the Late Permian to the Middle Norian, while the plutonic rocks, that intruded the Late Paleozoic and Scythian–Anisian sediments, have radiometric ages ranging between 262 and 212 Ma. Based on major and trace element content, the Permo-Triassic magmatic rocks originated by fractionation from primitive alkaline basalt to olivine tholeiite melts. Volcanic rocks are affected by hydrothermal alteration due to the sea water/rock interaction. Initial $^{87}Sr/^{86}Sr$ ratio of 0.703 and ä^{18}O of 5.6‰ in the most primitive rocks indicate upper mantle origin. Crustal contamination is indicated by the distribution of initial $^{87}Sr/^{86}Sr$ values between 0.704–0.707. Wide range of igneous rocks of Permian to the uppermost Triassic age shows evolution from the early intra-continental rifting to the advanced rifting and oceanization. While the Inner Dinarides experienced progressive rifting, followed by magmatic paroxysm in the Middle Triassic and oceanization in Jurassic (Palinkaš *et al.*, 2008), a huge carbonate megaplatform, resting as a part of Gondwana land and then separated from it, experienced disintegration, as a result of extensional tectonics in the Late Triassic/Early Jurassic time (Vlahović *et al.*, 2005). Permo-Triassic igneous rocks of the Dinarides represent a specific and autonomous palaeorift-related association (Pamić & Balen, 2005) and do not have equivalents in the recent oceans, in the Cenozoic African rift or in the Permian Oslo graben. Geochemistry of these rocks in the Inner and Outer Dinarides developed from within-plate, early rifting characteristics and gradually received MORB character by time. This change in geochemistry also reflects the different place of origin in relation to the axis of the Tethyan rift system.

2. Mainland field stops

2.1 Fužine, Gorski Kotar region: Hornblende andesite (Fužinski Benkovac quarry)

Eruptive rocks in the Fužinski Benkovac quarry, close to the village of Fužine were mentioned for the first time by Stache (1859): "*Ein echtes Eruptivgestein zu endecken, mit pophyrartig eingewachsenen Krystallen, eines weissen anorthischen Feldspates, so wie mit gut ausgebildeten wenn auch grössenteils sehr dünnen Amphybolkrystallen ... zwischen den Kalken und Dolomiten der Trias zu Tage gebracht hat*". It was confirmed by Kormos & Vogl (1913), who called it a diorite porphyre. Koch (1933) described an igneous body of diabase porphyry between Carboniferous sediments and Lower Triassic dolomites and thus suggested Middle Triassic age for that rock. Golub & Vragović (1975) never found thermal contacts between the eruptives and the surrounding sedimentary rocks. Their exploration revealed two eruptive bodies; the larger southern one, stretches from the village of Fužinski Benkovac to the village of Zlobin over a distance of 1800 m with 250 and 450-m widths. In the valley of Mala Voda creek, erosion dissected the igneous body for more than 240 m. The northern one is less elongated, about 1200 m long, and 400 m wide, stretching along the valley of the Lepenica creek. The two bodies were upon a time a single body, later dissected by a neotectonic fault.

The structure and texture of the eruptives is characteristic of subvolcanic effusive rocks. The phenocrysts of plagioclase and amphibole are evenly distributed within the groundmass. The basic hydrothermal processes are albitization and chloritization of primary minerals and recrystallization of the matrix. Epidote, zoisite, and calcite are also ubiquitous. The authors attributed alterations to deuteric and propylitic metasomatism.

Recent studies by Palinkaš *et al.* (*in prep.*) revealed hot contact with sandy sediments, rich in white mica and flora remains. Formation of the sediments in the high-energy water is recognized by oblique and cross bedding. Ar/Ar plateau age of two detrital micas samples yielded 342 ± 2.5 Ma and 341 ± 1.4 Ma ages with superimposing thermal effects at 310.2 ± 0.8 Ma, as well as 325.1 ± 0.8 Ma and 242.4 ± 3.7 Ma, respectively. The last age was obtained close to the contact of andesite with sandstone, thus corresponds to the age of intrusion of andesite into the Permo-Carboniferous clastic sediments.

2.2 Krka National Park (NP Krka)

Krka is one of the Croatian national parks, named after the river Krka. It is located in Central Dalmatia, in Šibenik–Knin county, downstream of Miljevci area and just a few kilometres northeast of the city of Šibenik. It was proclaimed as a national park in 1985 and it is the seventh national park in Croatia. It is intended primarily for scientific, cultural, educational, recreational and tourism activities (43°48' N, 15°58' E).

The landscape of NP Krka gives an expressive contrast between barren karst plateau area, cut by the Krka river canyon with green flora, flourishing on plentiful water supply. Visovac monastery from the mediaeval times, on a small islet in the mainstream, resisted turbulent times, and invaders of all kinds, keeping interesting collections of old books, paintings, frescos, etc. It was founded in 1445 during the reign of Ladislaus V, home of the Roman Catholic Franciscans near the village of Miljevci. The park also includes the Serb Orthodox Monastery Krka, which was founded in 1345 during the reign of Ludovic I of Anjou. This is a spiritual center of the Orthodox Dalmatian Eparchy (Diocese). It was first mentioned in a document from 1402 as the pious endowment of Jelena Šubić, the sister of Emperor Dušan. Ruins of fortresses, dating back to as far as the Roman times are at the nearby localities.

The Krka National Park belongs to the Southern European (Mediterranean and Sub-Mediterranean) floristic region. Due to its special position and the mosaic distribution of various types of habitats, it is characterized by exceptionally rich and varied flora and fauna. 860 species and subspecies of plants have been identified within the territory of the NP Krka, including several endemic Illyrian–Adriatic species. 18 species of fishes inhabit the Krka river, including brown trout and Dalmatian barbelgudgeon (*Aulopyge huegelii*) in the ecosystem. There are a number of amphibians and birds, and reptiles. The abundance of various species of birds (222), and the great significance of the Krka NP for spring and autumn migration make it the one of the most valuable ornithological regions in Europe. There are numerous carnivorous birds, notable ones like: osprey, short-toes eagle, golden eagle, Bonelli's eagle, lanner falcon and peregrine falcon, Eurasian eagle-owl, European bee-eater and griffon vulture. There are 18 species of bats as well, generally endangered or near extinction in the rest of Europe, long-fingered bat, Daubenton's bat and threatened European otter.

The major attraction is the river Krka and its travertine dam waterfalls like the Skradinski Buk, especially rich in water in winter and early spring (Fig. 2). The travertine dams develop from karstic water, with dissolved calcium carbonate, loosing CO_2 by mechanical degassing of the falling and splashing water, flora assimilation (lichens, mosses, algae, etc.), embracing calcium carbonate encrustations. The tuff behaves like a living organism, growing, but also dying by the upstream pollution caused by human activity. The 23.5 km long estuary is the mouth of the river Krka that flows into the sea. It is considered as an exceptional phenomenon, due to its

Fig. 2. Skradinski Buk cascades, Krka National Park.

lack of pollution and biological vitality. In the estuary of the Krka River, seawater extends to the base of the Skradinski Buk, one of the most attractive parts of the park. The special attraction is a cascade system and the waterfall Roški Slap (Fig. 3) located near Miljevci. The waterfall was named after the fortress Rog ('Horn' in English), now in ruins, once the property the mighty medieval Croatian noble family of Šubić. Krka river water powered a number of mills and flax mills for the local people in the past. In 1910 the first hydroelectric power plant was built on the Roški slap, being in continuous operation since then. Swimming and bathing in green water, bellow the waterfalls, is a special attraction, since the water has pleasant temperature in summer. It is an area rich in shellfish, freshwater fish, and saltwater fish. Skradin, a small, picturesque, stony Dalmatian village on the bank of the crystal clear water of the estuary offers good restaurants, and choice of food and wines.

Fig. 3. Roški slap, one of the tallest waterfalls in the Krka National Park.

3. Introduction to the archipelago field stops

3.1 The Mid-Adriatic islands, Jabuka, Brusnik, Vis, Biševo and Svetac

A beautiful pearl of the Adriatic islands, decorated by garlands of olives, vineyards, and drapery of conifers around old stony villages, embraced by the emerald blue-green water of the Adriatic, gives a visual joy to the geological and cultural program. The carbonate platform is a treasure of sedimentological phenomena, paleontological records, dinosaur footprints, recent carbonate deposition, exceptional hydrogeology, river estuaries, marshlands, national parks with great variety of flora and fauna. The lovely landscapes of the islands owe their impressions to the white carbonate rocks, but there are some unusual exceptions in the Adriatic scenery. Dark igneous rocks appear only on three Adriatic islands, Vis, Jabuka and Brusnik (Figs. 4, 5). As early as in the mid-19th century, these igneous rocks attracted attention of the Austrian geologists, who collected samples brought by fishermen (Hauer & Stache, 1862; Hauer, 1882). Professor Jiruš, a botanist, collected samples of volcanic rocks on Jabuka and Brusnik. The stones from Jabuka, collected by Jiruš, were described by Foullon as augitic diorite (Foullon, 1883). Mijo Kišpatić, mineralogist and petrographer, was the first to visit and study the islands. Kišpatić (1892) revealed the real nature of the rocks on Vis, Jabuka and Brusnik, but also those in the High karst zone, on the mainland at Knin, Vrlika and Budva.

In the following years, after Kišpatić research, Dalmatian islands ("Vis archipelago") attracted number of researcher, who contributed to the geology and petrography of the rocks on the volcanic islands.

Fig. 4. Jabuka island. A dark, unfriendly, almost 100-m high pyramid, which points threatening into the sky from the horizonless blue-green sea.

Fig. 5. Brusnik island. A low, serrated ridge, rising only 12 meters above the sea level, made exclusively of igneous rocks, with scarce endemic flora and fauna.

At Komiža, on Vis island, igneous rocks are in sharp contact with Triassic evaporites and Cretaceous limestones and dolostones (Carella, 1961), whereas in Brusnik and Jabuka just igneous rocks crop out. Because of their texture, Jabuka and Brusnik rocks have been commonly interpreted as intrusives, and classified as augite diorite (Foullon, 1883; Viola, 1894; Michel, 1916); diorite (Pelleri, 1942; Raffaelli, 1977), and augite albitite (Raffaelli, 1977). Several authors recognized an ophitic texture in these rocks and classified them as diabase (Martelli, 1908; Schubert, 1909; Cumin, 1921). Igneous rocks on Vis, however, were classified, besides augite porphyrite and melaphire by Kišpatić (1892) as diallagite (Martelli, 1908), diabase porphyrite and diabase (Michel, 1916). Carella (1961) named them as augite andesites and augite basalts, whereas Magaš *et al.* (1974) considered these rocks simply diabase and spilite.

3.2 Magmatism on the Mid-Adriatic islands

In a comprehensive work on the igneous rocks from Vis, Jabuka and Brusnik, Golub & Vragović (1975) distinguished two main groups: a) sub-volcanic types with augite diabase; b) extrusive types with augite andesite, spilite-keratophyre and spilite. The first group characterizes Jabuka and Brusnik, whereas the second one is found on Vis. The parent magma is, however, the same. Greenschist-facies submarine hydrothermal metamorphism affected the whole rock during their consolidation, producing albite–chlorite–prehnite–uralite–quartz overprint. A system of open fissures and cracks was filled by secondary minerals of the prehnite–pumpellyite group (Žunić, 1990).

3.3 Dating

The age of the Dalmatian Island magmatism, before introduction of radiometric dating, was esetimated on the basis of relationship between igneous rocks and sedimentary country-rocks. Raffaelli & Mamužić (1968) suggested a very young age for the igneous rocks at Brusnik, and regarded them coeval with fossil-rich conglomerates in the open fissures. Salopek (1939) considered volcanics on the Vis as Triassic, because of their close contact with Triassic evaporites. Šušnjar (1967) connected the Malm evaporitic succession with the magmatic rocks. Golub & Vragović (1975) considered them even older than the evaporites.

The first radiometric dating, and detailed mineralogical and geochemical study was done on the Jabuka Island rocks by Balogh *et al.* (1994). The Jabuka rocks are represented by an intrusion of two-clinopyroxene medium-grained gabbro, which derived from the crystallization of a slightly differentiated sub-alkaline magma. The K/Ar ages obtained on the whole rock and mineral fractions differ insignificantly. The average K/Ar age is 205 ± 6.9 Ma, and two isochrones gave 200.3 ± 7.9 and 199.5 ± 11.9 Ma with little amount of excess radiogenic Ar. It roughly reflects the latest stage of crystallization after intrusion. The research supports a tectono-magmatic hypothesis of a sub-alkaline, ensialic intrusion during the extensional processes of the continental crust, which occurred since the middle Triassic in the western Tethys. The dating, however, suggest uppermost Triassic, which does not correspond with the major phase of Triassic rifting, although the calc-alkaline character excludes MORB type lithotypes (Balogh *et al.*, 1994).

Garašić *et al.* (2001) suggested that the dolerite from Brusnik is a product of sub-alkaline magma. High content of Al_2O_3 and alkali elements point to its calc-alkaline character, as for other rift-related Permo-Triassic magmatics. Juračić *et al.* (2004) registered a small shoal made of a gabbroic rock (~10 m b.s.l., 2.3 km NW from Jabuka), which is in the line defined by the islands of Jabuka, Brusnik, Komiža, probably along a regional fault responsible for emplacement of the magmatic rocks.

Analyzing plagioclase separates of Jabuka and Brusnik rocks, De Min *et al.* (2008) obtained new Ar/Ar plateau ages of 227 ± 5 Ma and an isochron of 226 ± 3 Ma for Jabuka, and plateau age of 226 ± 3 Ma for Brusnik. So the age is "shifted" toward the Middle Triassic, which is a better fit to the general rifting conditions in the area.

Recent inspection and research of the Jabuka and Brusnik intrusives (Palinkaš *et al.*, 2010) revealed several novel discoveries, regarding presence of felsic dykes, pinkish in colour, which cut the intrusives for tens of meters. Thickness of these dikes is 10 to 30 cm. On Jabuka and Brusnik islands, they are characterized by the presence of well-developed crystals of potassium feldspars (Figs. 6, 7a). The dykes are a product of melt fractionation, and the coarse-grained, micropegmatitic texture suggests crystallization bellow a subvolcanic level. A number of secondary minerals (albite, uralite, epidote, prehnite, pumpellyite, fibrous hornblende, etc.) produced by hydrothermal alteration, as well as the presence of fluid inclusions in albite, confirms, however, engagement of sea water in the magma solidification and spilitization. Results of the chemical analyses done on the Jabuka and Brusnik gabbro and potassic-rich dykes that were affected by hydrothermal processes can hardly be taken as a reliable discrimination criteria due to intensive spilitization. A selection of immobile trace elements in the classification diagrams for volcanics after Winchester & Floyd (1977, Nb/Y–Zr/TiO_2,), and Pearce (1996, Nb/Y–Zr/Ti), and major elements for plutonic rocks, after Middlemost (1985, $N_2O/K_2O–SiO_2$), suggested basaltic andesite or gabbro diorite (monzodiorite) as the dominant petrologic lithotypes. The surprising fact is the age determined by Ar/Ar method on the gabbro, felsic dykes, and a coherent basalt fragment from Komiža on Vis island. Biotite (Fig. 7b) from the Jabuka gabbro gives a plateau age of 273 ± 1.1 Ma, with loss of Ar on 77.2 ± 2.4 Ma. K-feldspar from the Jabuka

Fig. 6. Jabuka island, felsic dyke.

gabbro is unaffected and shows similar value of 269.4 ± 2.3 Ma, but K-feldspar from the dyke on the Jabuka is dated at 254.5 ± 2.0 Ma. Biotite in the Brusnik dolerite is dated at 265 ± 1.1 Ma, while K-feldspar has plateau age of 214 ± 0.9 Ma, obviously lowered due to release of Ar, during some later thermal episode. K-feldspar separated from the basalt-andesitic fragment in the volcanics from Komiža, Vis island, gave a of 276.6 ± 1.7 Ma age coherent with that of the other magmatic formations. The ages determined on biotite are more consistant and differ from those obtained on K-feldspars, which was the object of the previous datings. This explans why the former K/Ar and Ar/Ar dating gave ages, which are not completely compatible with the geotectonic events in the early history of Tethyan evolution. Upper Permian ages correspond to the early intra-continental rifting and the geochemistry to the within plate magmatism.

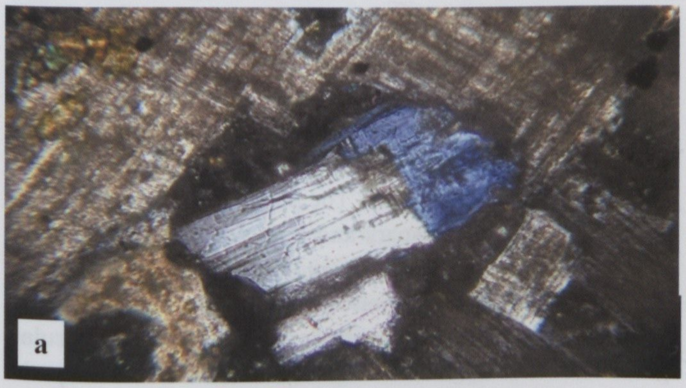
4. Archipelago field stops

4.1 Vis island

The fame of the island of Vis (Issa in old Greek, Lissa in Italian) goes very far back in time. Seafaring, fishing, olive trees, Mediterranean flora, abundance of aromatic plants imparting a special quality to honey, oranges, lemons, grapes, vines, climate without snow, etc. facilitated everlasting life on the island from prehistoric times, ancient Greeks, Romans, and Slaves in continuation of several thousands years. The area of Vis island is 91.6 km^2 and its highest point is the peak Hum (587 m).

Crnolatac (1953) described Vis island as a destroyed anticline, with Turonian dolomite in the core, and Turonian–Senonian limestones on the limbs. Evaporites of probable Triassic age crop out as diapirs, transgressively overlain by Cretaceous sediments close to Komiža village (Salopek, 1939). The deep oil-drilling "Vis" (1961-62) at Komiža recorded a 730-m thick series of magmatic rocks and evaporites lying above dolomites, anhydrites, marls, dolomite and limestone with cumulative thickness of 3688 m. The drill hole terminated in Malm limestones.

Donati (1750) was the first to noticed "some kind of serpentine" on the island of Vis. Fortis (1774) took a journey round the islands hoping to find some traces of volcanic activity, but disappointedly came to the conclusion that talk about black volcanic stone was the fruit of imagination of the local



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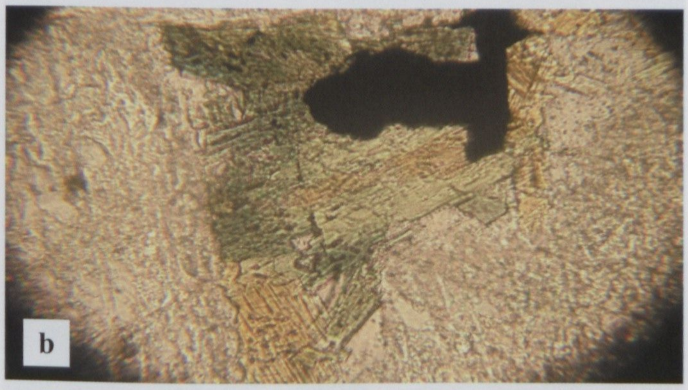

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Fig. 7. a) Microcline and clinozoisite, from the felsic dykes of Jabuka island, in thin section. b) Amphibole and biotite, mineral constituents of the Jabuka gabbro, in thin section. K-feldspar offers possibility to be dated by Ar/Ar method, but results give incoherent values in comparison to biotite ages, due to poor argon retention of its crystal structure.

people. The fact is, that Komiža (Fig. 8), a small fishing village on the western side of Vis island (43°2' N, 16°5' E), is sitting on a volcanic ash and lava (Fig. 9).

The first competent description of the igneous rocks of Vis came from geologists of the State Geological Institute in Vienna, F. von Hauer and G. Stache, in connection with the geological mapping of the Austro-Hungarian Monarchy (1861–1862). They recognized melaphirs, tuffs and volcanic breccias. Hauer (1867a) also found a prehnite pebble in the gravel on the beaches of Komiža. Hauer's first chemical analysis of the Komiža volcanic rocks (1867b) confirmed their similarity with gabbro.

Fig. 8. Komiža, fishing village on the western side of Vis island.

Fig. 9. Vis island. Volcanoclastics at Komiža bay.

Volcanic rocks in Komiža are situated near the church of St. Nicholas (Sv. Nikola), along the coast, from the fish cannery all the way to Pištica bay. Kišpatić (1892) made distinction between the tuffs and augitic porphyrite, describing and distinguishing mineral content of the phenocrysts, 4 mm long feldspars, dark-green augite, and volcanic glass, microcrystalline groundmass of augites, magnetites and feldspars. The tuff has the same composition but alteration of the primary minerals is the dominant process.

Peculiarities of the lava flows on Komiža are spheroidal jointing and amygdaloidal texture. The amygdules, former gas bubbles and vesicles, are big enough to accommodate a number of hydrothermal minerals like chlorite, quartz, calcite and acicular aragonite. Among them stands out the pale-green prehnite with appreciable size and gemstone quality at places (see below Fig. 13).

4.1.1 Marine lava flow on Vis island near the village of Komiža

Volcanic rocks on the island of Vis are situated around the small village of Komiža, near the church of St. Nicholas (Sv. Nikola), along the coast, from the fish cannery all the way to Pištica Bay. Golub & Vragović (1975) already distinguished sub-volcanic types on Brusnik and Jabuka and extrusives on Vis near Komiža represented by augite andasite, spilite-keratophyres and spilites. The parent magma is, however, the same. The eruption might have come from the same magma chamber in two separate phases. The crystallized rocks are of almost the same composition, but different textures, due to different cooling regimes. According to Golub & Vragović (1975) extrusives from Komiža can be classified into four rock types:

4.1.2 Augite andesite from the quarry close to St. Nicholas chapel

The rock has dark grey, grey-greenish, to brown-greenish colour, homogenous structure, conchoidal and spheroidal joints and porphyritic texture. The phenocrysts, observable by the naked eye, are feldspars and dark pyroxenes. At places, spheroidal joints with its its amygdaloidal texture could have derived from magma that introduded into sediments close to the surface, and the fine-grained, partially glassy, vesicular, spherulitic and amygdaloidal varieties of the same rock probably derived from submarine lava flows. In thin sections, more or less altered phenocrysts of plagioclases (60 to 84% An), augite (diopside and ferroaugite), magnetite and ilmenite. The devitrified (felsitic) groundmass is full of chlorite (viridite), zoisite, epidote, hematite, limonite, albite, sericite, prehnite, leucoxene and quartz, developed by the greenschist-facies submarine hydrothermal metamorphism, which affected the whole rock during their consolidation, producing albite-chlorite-prehnite-uralite-quartz overprint. The plagioclase microlites are more acid (35 to 50% An). A system of open fissures and cracks, was filled with secondary minerals of the prehnite–pumpellyite group (Žunić, 1990).

4.1.3 Augite andesite near Pištica bay

The andesite of this locality has homogenous structure, irregular joints and spheroidal disintegration by weathering. The colour is dark grey with slight green hues at places. The texture is porphyritic with hyalopilitic to pilotaxitic groundmass, achieving sporadically intersertal features. The outcrops suggest a superposition, augite andesite at the base and volcanic aggregate on the top.

The phenocrysts are rare, and microlithic groundmass dominates. Plagioclase (76 to 84% An) shows more basic character then the microlites (andesine). Alteration products are chlorite ("viridite"), pumpellyite, prehnite and coarse-grained calcite.

4.1.4 Spilite-keratophyre from the close to St. Nicholas chapel

The dark grey, brown, almost black, aphanitic rock with rare scattered plagioclase phenocrysts has homogeneous structure, but sporadically shows pseudo-stratification with fluidal or micro-amygdaloidal structure. The texture is porphyritic with rare phenocrysts of albite and augite in a holocrystalline pilotaxitic or pseudo-trachitic groundmass consisting of microlites (albite, pyroxene, chlorite, iron oxides, quartz) due to recrystallization from the former hyalopilitic texture. The scarce feldspar microlites were altered to prehnite and pumpellyite. Augite as a phenocryst has inclusions of tiny zoisite and epidote crystallites. The amygdales are usually not bigger than 0.5 mm, but rarely their diameter reach 1 mm. Amygdales are filled up with quartz, chlorite albite, and prehnite.

4.1.5 Volcanic agglomerates, lapillistones, lapilli tuffs, tuffs

Large masses of volcanoclastics are situated along Komiža bay (Fig. 9–11). The rocks should be considered pyroclastics, because they do not show evidences of transport or re-deposition of juvenile particles. On the other hand, the boundary between the blocks and the fragments and the groundmass is a reaction rim formed by alteration processes of aquatic origin. It implies lava flow in shallow marine environment, rather than origin from subaerial fallout tephra. At places, the blocks

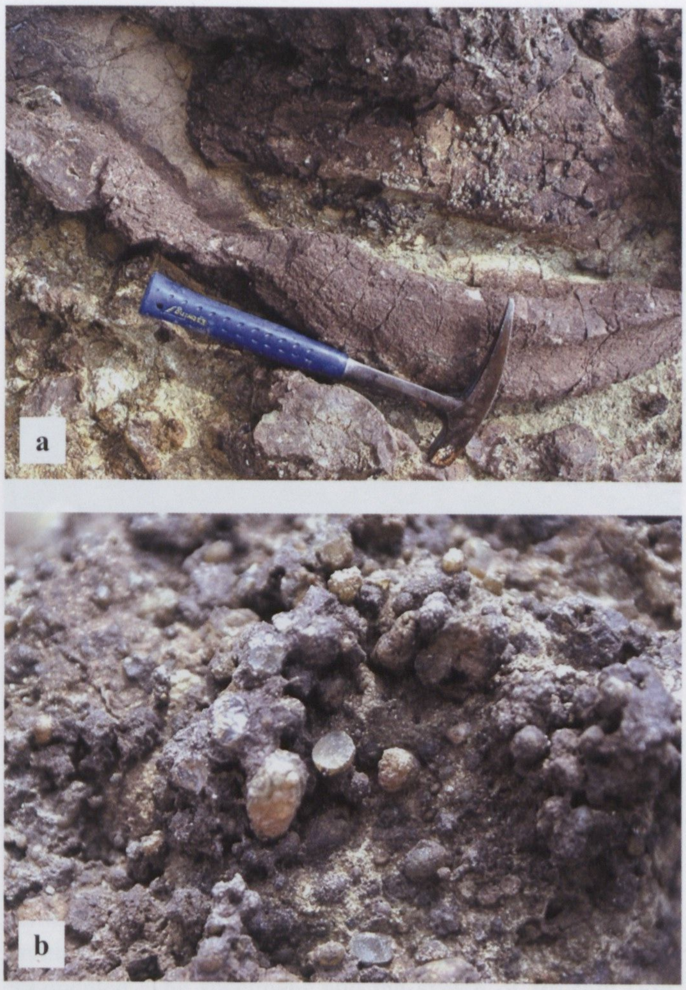

Fig. 10. a) Lava lob; quenched lava flow with tuffaceous reaction rims and prehnite globules. b) Detail of Fig. 10a, globules of prehnite, a product of seawater interaction with hot lava flows.

resemble to bombs, at others they assume the shape of pillows. Rare pillow lava lobs supports submarine lava flow as well (Fig. 10a.) Andesitic lava, rich in volatiles and having lower viscosity, produced degenerated pillows, or rather pseudo-pillows, whose formation was suppressed, and subjected to severe fragmentation (Fig. 12). Hyaloclastite, formed by autobrecciation, and vesiculation should be the proper term for the rocks.

The blocks and the fragments of the volcanic agglomerates show wide varieties in roundness, texture, structure and mineral content. Their colour varies in several hues of green, grey, brown, dark green, violet-brown and almost black, depending on the degree of oxidation and alteration of ferromagnesian minerals into chlorite (viridite). The structure is vesicular and amygdaloidal, the diameter of the amygdaloids varies from mm to cm. The major minerals are albite and augite. Zoisite, epidote, magnetite, ilmenite, prehnite, quartz, chlorite, pumpellyite, sericite, titanite and calcite are alteration products. The texture is primarily porphyritic with small phenocrysts approaching the size of microlites. The texture of the groundmass is hyalopilitic, intersertal, variolitic, and ophitic or diabase. The groundmass is completely opacitized and devitrified.

Fig. 11. Vis island. Outcrop of volcanoclastics at Komiža bay.

Fig. 12. Vis island. "Pseudo-pillow" in andesitic lava.

The cement and matrix of the volcanic agglomerates, lapillistones, and lapillituffs and the tuff itself is earthy, semi-friable groundmass with grey-greenish or dark green colour and with more or less amygdaloidal structure. Amygdales are commonly less than 1 mm, but rarely exceed 0.5 cm. The major minerals are augite and albite, in the groundmass chlorite (viridite). The amygdales are filled by chlorite, prehnite and calcite in radial patterns.

4.1.6 Prehnite as a gemstone

The erosion of pyroclastics along Komiža beach creates a marvellous pebble beach. Larger fragments contain numerous amygdales or vesicules, with alteration products, but prehnite in the semi-filled vesicules or vugs attains a remarkable size and attractive pale green colour and achieves gemstone quality (Fig. 13). It occures as a secondary mineral together with albite, quartz, calcite, pumpellyite and chlorite (Šćavničar *et al.*, 1975).

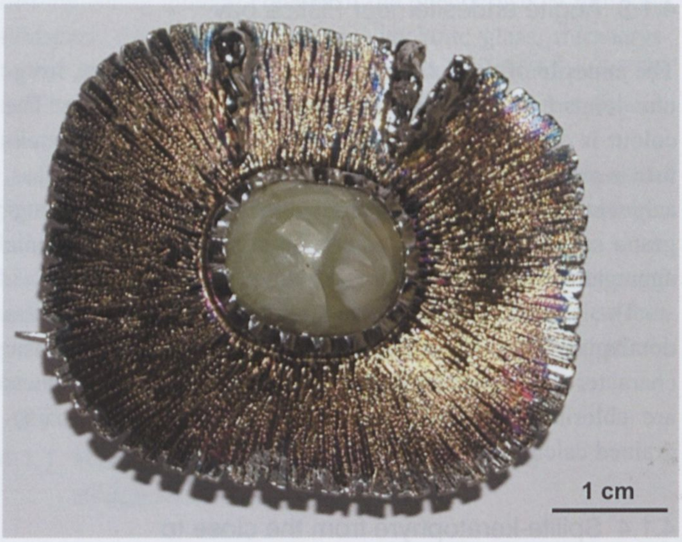

Fig. 13. Pale-green prehnite of gemstone quality, fixed in a feathery silver garland, makes an attractive brooch.

The crystals of prehnite are elongated parallel to the *a* axis and are often tabular owing to the predominant development of {001}. The {010} faces are striated parallel to the *a* axis due to the presence of the narrow {011} faces, as shown by optical goniometer measurements (Žunić *et al.*, 1990). The crystal structure of prehnite, $Ca_2(Al,Fe)(OH)_2(Si_3AlO_{10})$ has been refined in the space group *P2cm* (a = 4.646(2) Å, b = 5.491(3) Å, c = 18.52(3) Å, Z = 2) Si and Al showed a completely ordered distribution in the structure. The obtained Fe–Al substitution for the octahedral co-ordination is 17%. No monoclinic domains could be observed in the crystals. Laue photographs show that the splitting of the diffraction maxima in the prehnite from Komiža is due to lattice rotation around the direction of the *b* axis.

4.2 Biševo island

Biševo island (42° 58' N, 16° 01' E) is located about 4.5 km from Vis. Its surface area is 5.84 km², the highest point is 240 m a.s.l.. The island is depopulated at present. Bisevo is famous about a spectacular "Blue Cave", drowned in the seawater and illuminated by the sunlight penetrating through an underwater opening. The optical impression creates a dark amphitheater,

Fig. 14. Biševo island, "Blue Cave".

Fig. 15. Brusnik island. The strand on the northwestern side.

above a deep blue, fluorescent pool and shiny silvery objects submerged in the water (Fig. 14). The islet is made of Lower and Upper Cretaceous limestones and dolomites, and Eocene foraminiferous limestones and marls, which transgressively lying abovethe Upper Cretaceous carbonates.

4.3 Brusnik island

Brusnik is a low, serrated ridge, rising only 12 metres above the sea level (43°00' N and 15°48' E). It is 3 km southeast of the island St. Andrija. In the very centre of Brusnik island, there is a small hollow, partially filled with sea water. The strand on the northwestern side of Brusnik, facing St. Andrija island, is made of pebbles and huge boulders, up to 50 cm in size (Fig. 15). The scenic boulders, with perfect rounded shapes, due to perpetual marine abrasion, was used as ballast in fishing boats. Therefore, they were distributed around other Adriatic islands, found in some caves as firestones, confusing geologists and archaeologists on their origin. The name Brusnik ('grindstone' in English) suggests the use of the rough stone surface as a grindstone.

The first information about the rocks of Brusnik came from Hauer (1867b), based on the description of conglomerate and pebbles brought by fishermen to Komiža. Carbonate cement in the conglomerate contains rich fossil community with mollusc shells, still reddish in colour. Besides, the cement contains snails, fragments of bryozoans, spines of sea urchins, and corraline algae, very well preserved or at places fragmented. The specimens and the sketch of Brusnik (Fig. 16) that were sent to Hauer in Vienna lead him to the conclusion that the igneous rocks must be very young. Ten years after Jiruš's research on Brusnik, Mijo Kišpatić explained the phenomena as an evidence of fairly recent uplift of the island. The high position of cemented conglomerates and breccia with fossils (close to the top of the islet ridge) as fissure fillings in the solid diabase attest, however, the dynamic eustatic fluctuation of the Adriatic Sea during the Quaternary. By the

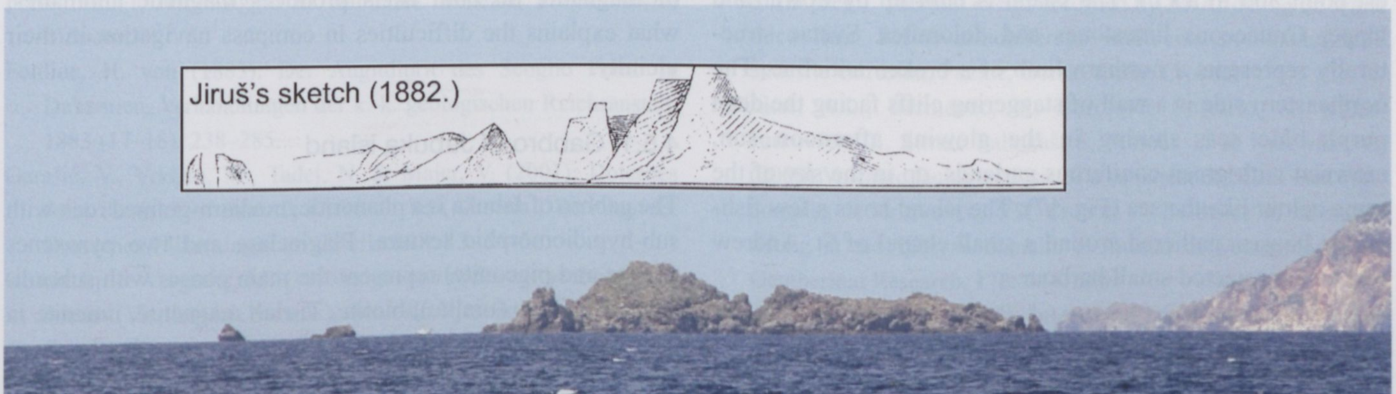

Fig. 16. Sketch of Jiruš from 1882, compared with a photo taken recently, approximately from the same position.

microscopic investigation of the rock Kišpatić (1892) determined feldspars, augite, quartz, magnetite and its transformation into hematite, as well as amphibole and biotite as alteration products of augite. He also made a definite distinction between the texture of Brusnik and Komiža igneous rocks, classified the former as diabase, being similar to the Jabuka gabbro, and the latter as volcanics. His all-around interest on the nature of the island, described sparse vegetation and the famed black Brusnik lizard (*Podarcis melisellensis pomoensis*), and some plants (*Centaurea jabukensis and Centaurea crithmifolia, both Asteraceae*), which are protectic endemics.

4.3.1 Dolerite of Brusnik island

The dolerite has phaneritic, holocrystalline, intergranular diabase texture with ophitic to sub-ophitic groundmass (Garašić *et al.*, 2001). Mineral composition is plagioclase, albite, pyroxene, amphibole, biotite, chlorite, sericite, prehnite, epidote, titanite, quartz, calcite, pyrite, magnetite, ilmenite, hematite, and leucoxene, *i.e.* the same as in the Jabuka gabbro. Plagioclase composition varies from An 66–88 to An 4–10. Amphibole is secondary (actinolite, ferroactinolite, and magnesiohornblende) and it is associated with biotite and chlorite (brunsvigite, pycnochlorite to diabantite). Sericite replaces plagioclase grains. Golub & Vragović (1975) described this rock as spilitized augite diabase. The high content of Al_2O_3 and alkali elements points to calc-alkaline character. Major and trace elements are comparable with Triassic magmatic rocks of Alps, Dinarides and Hellenides, developed in an extensional environment of aborted rift (Garašić *et al.*, 2001).

4.4 Svetac island

The island of Svetac (St. Andrija) or simply Svetac ('Saint' in English), which in contrast to the Brusnik, is made of Cretaceous carbonates is located between Brusnik and Jabuka, 24 km from Komiža (43°20' N, 16°00' E, area 4.6 km^2, highest point 305 m a.s.l.). The island is built up by Lower and Upper Cretaceous limestones and dolomites. Svetac structurally represents a northern limb of a broken anticline. The northeastern side is a wall of staggering cliffs facing the deep purple-blue sea, shining in the glowing afternoon sun, crowned with green coniferous garlands, up in the sky of the same colour like the sea (Fig. 17). The island hosts a few fishermen houses, gathered around a small chapel of St. Andrew and an unprotected small harbour.

Fig. 17. St. Andrija (Svetac) island.

4.5 Jabuka island

Jabuka island ('Apple' in English, Scoglio Pomo in Italian) astonishes a visitor by its hundred meter (96 m) high, dark unfriendly pyramid, pointing threatening into the sky from the horizonless blue-green sea (Fig. 4). The island, with no place to land or embark on a boat or vessel (surface area ~0.02 km^2), is located 50-km northwest of the island of Vis (43°05' N, 15°25' E). Its dark colour, in contrast to the other white Adriatic islands, is due to the rocks formed by chilled magma, forcing its way through sediments of the seabed. The remnants of volcanic activity is a medium- to coarse-grained gabbro, a conduit of magma, while peripheral dykes, sills, lava flow, *etc.* are obliterated by long-term erosion.

Kišpatić (1892) himself, the first to study systematically igneous rocks from the islands, never actually got to Jabuka island. He obtained rock samples from the local administration in Komiža, to be exposed on the show at the Economic Exhibition in Zagreb, 1891. He confirmed the similarity with the rocks from Brusnik islet. By visual inspection and microscopic examination he revealed the mineral composition as plagioclase, augite, "iron ore" (= magnetite), "titanium ore" (= ilmenite) and apatite. Amphibole, biotite and chlorite originated by alteration of primary magmatic minerals. Kišpatić named the rocks of Jabuka augitic diabase. The large quantity of magnetite on both islets produces magnetic anomalies, what explains the difficulties in compass navigation in their vicinity.

4.5.1 Gabbro of Jabuka island

The gabbro of Jabuka is a phaneritic, medium-grained rock with sub-hypidiomorphic texture. Plagioclase and two pyroxenes (augite and pigeonite) represent the main phases with subordinate amphibole (uralite), biotite, Ti-rich magnetite, ilmenite in decreasing order of abundance. Plagioclase mostly shows an oscillatory zoning, ranging from An57 Ab41 to An75 Ab23. Flakes of sericite largely occur within the plagioclase crystals. Pyroxenes are mostly represented by pale-green unzoned augites (En 41–45%, Fe 16–22%, Wo 36–39%) and minor colourless magnesium pigeonite (En 57–59%). Uralitization converted pyroxenes to ferroactinolitic hornblende. Chlorite and fibrous secondary amphibole are a product of late-stage hydrothermal alteration (Balogh *et al.*, 1994). The trace elements and normalized-MORB incompatible element spider diagrams support the similarity of the Jabuka gabbro with continental tholeiitic magmas, and exclude MORB-type affinity.

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Appendix – Itinerary for IMA 2010 HR1 Field trip

Friday, August 27, 2010 (Day 0), Travel from Budapest to Zagreb (Samobor)

14.00–17.00	Travel from Budapest to Samobor, a picturesque village near Zagreb
17.00	Samobor, accommodation in the pleasant small hotel “Lavica”

Saturday, August 28, 2010 (Day 1), Travel from Samobor to Split (Lečevica)

08.00–10.00	Travel to Gorski Kotar region, close to Rijeka
	Field stop 1: Fužine andesite quarry, carbonate platform environment
11.30–13.30	Travel to the Krka National park through Vratnik pass, via Senj and Zadar
	Field stop 2: Krka National park, Skradin village, boat tour in the estuary of the Krka river, travertine cascades, waterfalls, swimming, bathing
17.30–18.30	Travel to Lečevica, eco-village near Split, dinner and accommodation in countryside style in private pension “Melvan”

Sunday, August 29, 2010 (Day 2), Travel from Split harbour to Vis island

09.00–11.20	Split harbour, ferry to Vis island
11.20–12.20	Travel from the town of Vis to Komiža (on Vis island)
12.20–14.20	Accomodation in the private apartments, rest
14.20–17.20	**Field stop 3**: Submarine lava flows, andesite, spilites, keratophyres, volcanic agglomerates, lapillistones, lapilli tuffs, tuffs, prehnite pebbles, evaporites, etc
18.00–	Dinner

Monday, August 30, 2010 (Day 3), Sea cruise to the islands Biševo, Brusnik and Svetac

08.00–09.00	Travel, sea cruise to Biševo island
09.00–10.00	**Field stop 4**: Blue cave
10.00–11.00	Travel to Brusnik island
11.00–14.00	**Field stop 5**: dolerites, gabbros, dykes, flora and fauna, beach abrasion, cobbles
14.00–18.00	Travel to the island of Svetac
18.00–	Anchoring, resting in the bay of the island Svetac, swimming-bathing, barbecue grill, wine, etc., overnight stay on the boat

Tuesday, August 31, 2010 (Day 4), Travel to Jabuka island and return to Komiža in Vis island

08.00–12.00	Travel to the island of Jabuka
12.00–15.00	**Field stop 6**: Landing on the island or cruising around in case of rough sea
15.00–19.00	Return to Komiža
20.00	Dinner, accommodation in Komiža

Wednesday, September 1, 2010 (Day 5) Return to Budapest

06.00	Travel from Komiža to Vis town
07.50	Embarkment on the ferry to Split
14.20	Arrival to Split and leaving toward Budapest via Zadar, tunnel through Velebit Mts., via Zagreb